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Analysis of the PM2.5 Distribution and the Transfer Characteristic in a Car-Cabin

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Abstract

In order to investigate the transfer characteristics of PM2.5 in a car-cabin, several experiments were done through real-time online monitoring the concentration of PM2.5 and CO_2 in the car-cabin under different ventilation modes (Circulation with the outdoor air and Recirculation without fresh air) under the minimum of mechanical ventilation and the same experimental route condition. PM2.5 concentration distribution characteristics and the ratio of inside to outside concentration I/O were analyzed. The ventilation rate was determined by the CO_2 concentration change during the experiment and further was used to analyze the transfer characteristic of PM2.5. The results showed that under the circulation with the outdoor air condition, average I/O is 0.6, while it is 0.25 under recirculation condition. I/O value increases with the increase of the driving speed. It could be concluded that ventilation mode have a significant impact on the cabin concentration of PM2.5 and plays a decisive role in PM2.5 levels in the car-cabin. The quantitative evaluation PM2.5 transfer characteristic analysis under circulation with outdoor air condition shows that the ventilation, penetration and deposition accounted for 69.3%, 22.8%, and 7.9%, respectively. While under recirculation condition, penetration accounted for 72%, and deposition accounted for 28%.

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Keywords: Car cabin environment; PM2.5; I/O; Transfer characteristic

1. Introduction

At present, the problem of air pollution is grim in China, especially the regional air pollution of respirable

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particulate matter (PM10) and fine particulate matter (PM2.5), which has become increasingly prominent [1, 2], and has a bad effect on people's health, social harmony and stability. The outdoor atmosphere can't be effectively controlled in the short term, so it is very important to keep a good indoor environment.

Cars have been an important transport means for people, approximately 90% of US commuters driving to work [3]. The atmosphere PM2.5 pollution situation gradually becomes serious. A tracking survey of nearly ten thousand people by the US Environmental Protection Agency (EPA) in 1993-1994 shows that people spend about 7.2% of the time in a vehicle [4]. A large amount of particulate matter is exhausted from the moving cars. As a result, it is much worse for driver exposure to pollution in the road environment than the city background [5, 6]. It has been found that the exposure of PM 2.5 in cars exceed 30% that in residential environment [7]. Karanasiou et al. [8] also found the exposure to particulate matter in cars is higher than other modes of transportation. Further experimental research at the Los Angeles road showed that exposure to ultrafine particles of vehicles accounted for 33 - 45% to total daily exposure [9], Lee et al. [10] also pointed out that ultrafine particle exposure accounted for 10%~50% to the exposure in car microenvironment on one hour a day commuting basis. Xu and Zhu [11] analyzed the impact of ultrafine particles I/O factors with mass balance modeling. Hudda and Fruin [12] established an empirical model to predict I/O ratio, the model parameters including of the vehicle age, speed, volume, and car ventilation mode setting. It can be concluded that there are much difference about the exposure to PM2.5 both inside and outside of the cars in different countries and regions. A lot of researches were done on exposure to particulate matter in vehicles on the road. However, quantitative research on the factors influencing the concentration of PM2.5 in car-cabins is very limited.

This study investigated the transient PM 2.5 concentration by experimental and theoretical methods. The field measurement was conducted to record particulate matter concentration. Based on the experimental data, the temporal PM 2.5 concentration characteristics and the I/O ratio were studied. The transport mechanism of PM 2.5 in car environment was also analyzed by quantitative method.

2. Methods

2.1. Experimental measurements

In this paper, the experiment was conducted in Tianjin, a city with serious air pollution in northern China. The roads in the center of the city were selected and the measuring route was shown in Figure 1(a) represented by the black solid line. Chinese air quality monitoring analysis platform indicated that particulate pollution was more serious from December to February in Tianjin. The time with pollution situation was 73.5 percent in this period and the primary pollutant was fine particulate matter (PM2.5) [13]. So this experiment was conducted from December, 2014 to February, 2015. A VW Passat private car with the vehicle age of 4 years was chosen as the experimental platform. The volume inside is about $3m^3$and the automotive filter and air conditioning system are equipped in this car.

An integrated sensor named FengSensor developed by Zhi Lian Tong Building Technology (Beijing) Co., Ltd. was adopted to measure the temperature, humidity, PM2.5 concentration and CO_2 concentration continuously. In this paper, the FengSensor had been calibrated and the sampling frequency is1/60 Hz. The measuring range of the PM2.5 sensor installed in the FengSensor is 10-900μg/m3.The accuracy of the PM2.5 sensor is ±10μg/m3 ± 5% of readings and the measuring size is 1.0-2.5um.The measuring range of the CO_2 sensor installed in the FengSensor is 0-5000ppm. The measurement accuracy is ±75ppm±3% of readings. Pouyan et al. [14] found that the distribution of the particulate matter concentration was almost uniform in the car. So a measuring point was set in the co-pilot position as shown in Figure 1 (b).In order to ensure the accuracy of the measurement, the measurement started when the ventilation in the car was steady. In the experiment, we kept the windows and doors closed. Two ventilation modes were adopted to conduct this experiment. One was circulation with the outdoor air (case 1) and the other was recirculation without the fresh air (case 2).

The filter in the car was taken down to measure efficiency of PM2.5in the testing platform of air filter. In the testing platform, the US Metone 2400 laser particle counter was applied. The sampling flow is 28.3L/min. Six kinds of particle size channels including<0.3um, 0.3-0.5um, 0.5-1.0um, 1.0-3.0um, 3.0-5.0um and 50-10.0um were utilized simultaneously. The overlapping loss of Metone 2400 is less than 5%per 400,000 particles / Ft3.

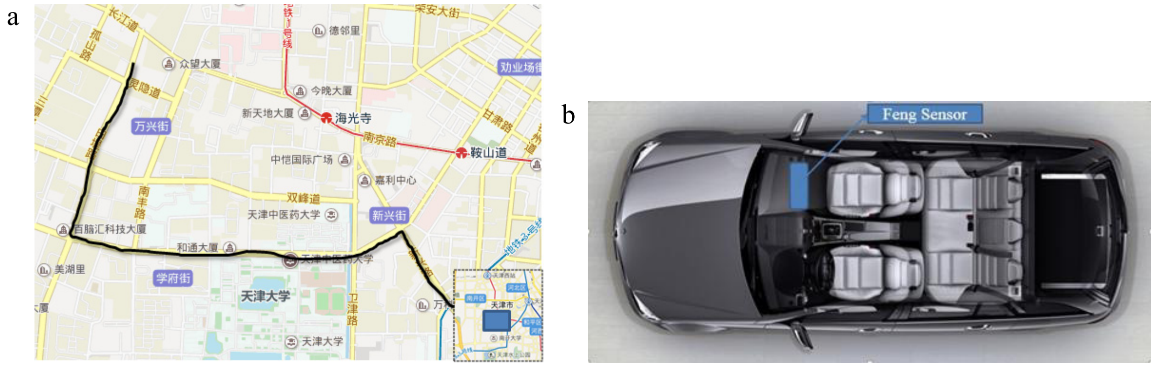

Fig. 1. (a) Experimental area and Route; (b) Measuring platform and position

2.2. The transport model

Switzer and Ott [15] derived a mass balance model to simulate indoor and in-vehicle microenvironments. A similar mass balance model is derived based on the schematic of the vehicle cabin and heating, ventilating, and air conditioning (HVAC) system [16]. The transport models of PM 2.5 in this paper are developed based on the mass balance model and the experimental conditions, to analyze the temporal PM 2.5 concentration characteristics. The schematic of the car cabin, ventilating, and HVAC system is shown in Figure 2. The models are based on the following assumptions: (a) the vehicle cabin is a well-mixed zone with a uniform PM2.5 concentration; (b) the filter removal efficiency for the HVAC system is a constant irrespective of time or particle concentration; (c) the deposition rate does not change with time or direction.

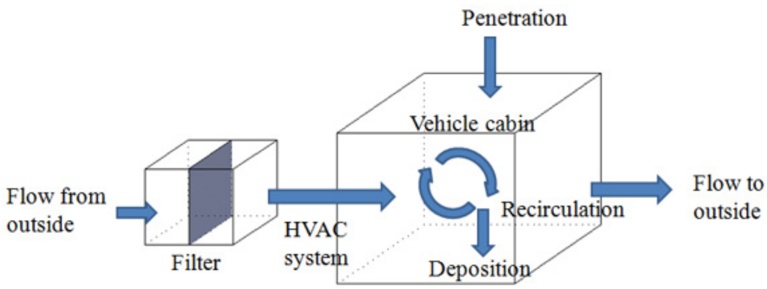

Fig. 2. Schematic of air flow through the vehicle cabin, ventilating, and air conditioning (HVAC) system.

In case 1, particles enter the vehicle cabin by infiltration through cracks, and advection from the HVAC system. Particles are removed from the vehicle cabin by exfiltration through cracks, advection to the HVAC system, and deposition to surfaces inside the vehicle. The transport model for the case of the HVAC system using outside air is:

$$\frac{dC_{in}}{dt} = \lambda_{hvac}\left[C_{out}(1-\eta) - C_{in}\right] + \lambda_{\inf}(C_{out} - C_{in}) - \beta C_{in} \tag{1}$$

In case 2, particles enter the vehicle cabin due to infiltration through cracks. Particles are removed from the vehicle cabin by exfiltration through cracks condition and deposition to surfaces inside the vehicle. In the case for recirculation of cabin air, the mass balance is:

$$\frac{dC_{in}}{dt} = \lambda_{\inf}(C_{out} - C_{in}) - \beta C_{in} \quad (2)$$

Where C_{in} is PM2.5 concentration in the vehicle (μg m^{-3}). C_{out} is PM2.5 concentration surrounding the vehicle exterior (μg m^{-3}). λ_{hvac} is air exchange rate for the HVAC system (h^{-1}). λ_{inf} is air exchange rate due to infiltration through vehicle cracks and windows (h^{-1}). V is passenger cabin volume (m^3), $3m^3$; η is filter removal efficiency, fraction. β is deposition rate(h^{-1}). C_{in} and C_{out} are experimental data. η is measured on experimental platform, 30.1%. β is worked out by the transport models, 0.52± 0.40 h^{-1}(case 1) and 0.68 ± 0.11 h^{-1}(case 2).

According to the transport models, λ_{hvac} and λ_{inf} need to work out. A series of laboratory and field measurements were conducted to use the carbon dioxide produced by people as a natural tracer gas for air exchange rate measurements in homes [17, 18]. This method is utilized in this paper based on continuous monitoring of CO_2 in the car. Carbon dioxide is produced as a part of human metabolism. The emission rate (FR, ml/s) depends on the level of activity (M, W/m2), height (H, m), weight (W, kg) and respiratory quotient (RQ, 0.83) [19]:

$$FR = \frac{RQ(0.71H + 0.0133W - 0.1917)M}{21(0.23RQ + 0.77)} \quad (3)$$

The variation of CO_2 concentration between two measurements performed with time interval of Δτ in a point can be expressed from the instantaneous flow rate equation as:

$$\frac{FR}{V[c_{in(k-1)} - c_{out}]} - \frac{c_{in(k)} - c_{in(k-1)}}{\Delta\tau[c_{in(k-1)} - c_{out}]} = \frac{\lambda}{3600} \quad (4)$$

Where FR is equal to 11.478 (ml/s).λ is air exchange rate (h^{-1}); Δτ is the time interval (s); C_{in} (k) is CO_2 concentration for a moment; C_{in} (k-1) is CO_2 concentration for the former moment; C_{out} is CO_2 concentration for the urban background.

3. Results and discussion

Different ventilation modes, the concentration of PM2.5 inside and outside the car is shown in Figure 3 (a) and (b). In case 1the I/O value is about 0.6, and the PM2.5 concentration exceeds 2-4 times the national standard limited value of 35μg/m³ (GB 3095-2012). This indicates that outside PM2.5 is the main contribution to the high cabin PM2.5 concentration. In case 2, the car I/O value of PM2.5 is about 0.3, indicating that the vehicle body could block entry of PM2.5.Comparingthe two figures, we can conclude that the influence of ventilation mode on the I/O values and PM2.5 concentration levels inside the vehicle is significant.

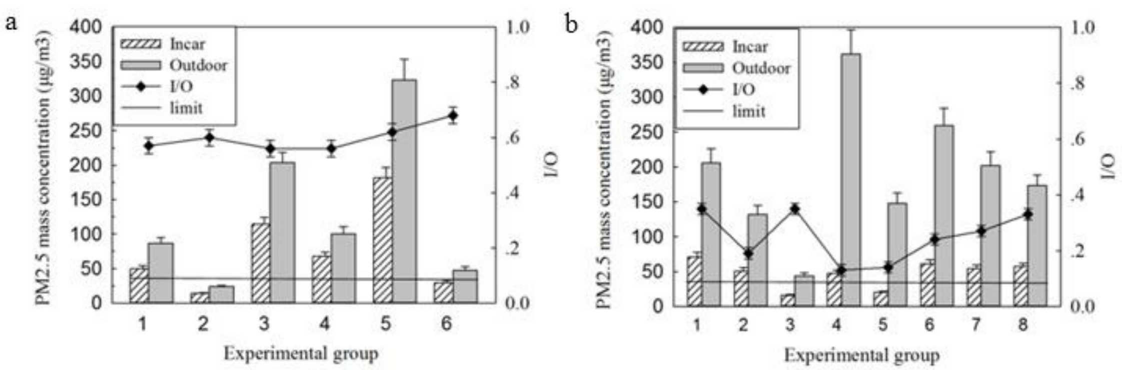

Fig. 3. PM2.5 concentration inside and outside the vehicle and I/O. (a) Case 1; (b) Case 2

This study utilized the transport model combined with experimental data to analyze the particle distribution characteristics under different ventilation settings quantitatively. Ventilation rates could be obtained according to CO_2 concentration change, as described in Figure4 (a) and (b). In case 1, air exchanges rate is 27 ± 3.3/ h and the in-car air is strongly diluted. In case 2, air exchanges rateis3.6±1.6/ h. CO_2 accumulated rapidly in the cabin, and it went beyond the national standard 5-6 times (GB/T18883-2002, 1000ppm).

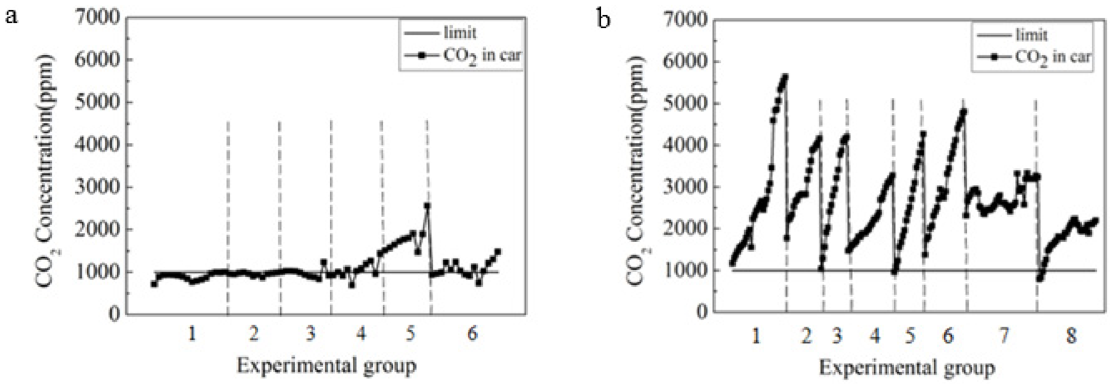

Fig. 4. CO2 concentration in the vehicle. (a) Case 1; (b) Case 2

Figure 5 shows the quantitative evaluation results. The calculated data of all the experimental groups are consistent to some extent. In case1 (Figure 5(a)): the PM2.5 percentage of passing through the filter, infiltration and surface particle deposition was69.6% ± 4.8%, 22.2% ± 3.3 % and 7.7% ± 2.0%, respectively. It could be concluded that the main impact on the car environment of PM2.5 is due to mechanical ventilation, followed by deposition and infiltration. In case 2(Figure 5(b)), the PM2.5 percentage of infiltration and surface particle deposition was 72.5% ± 4.7% and 27.5% ± 4.7%.

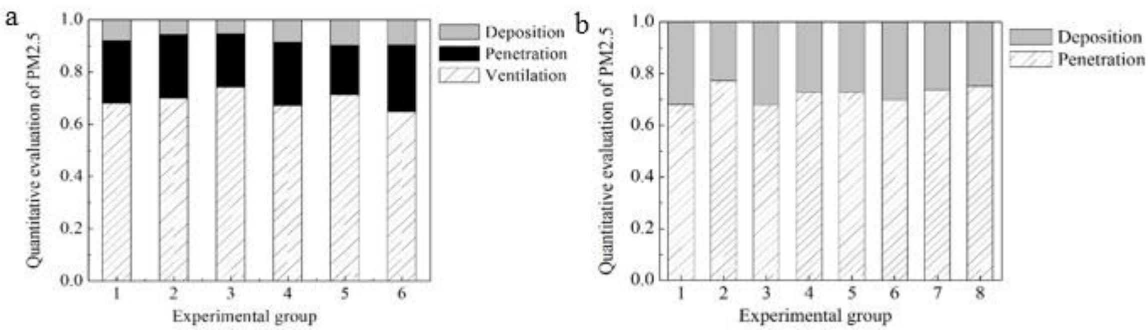

Fig. 5. PM2.5 transfer characteristics of the vehicle. (a) Case 1; (b) Case 2

We found that the air filter plays a decisive role in the control of PM2.5 concentration in case 1, and the effect of infiltration is limited. Under the recirculation condition, strengthening the car body's tightness is essential to PM 2.5 control.

4. Conclusions

It could be concluded that air exchange rate increases with the increase of the driving speed. Under the experiment condition, air exchange rate of case 1 is about 9 times higher than case 2.

Different ventilation modes have different effect on the PM2.5 concentration and the I/O ratio in the car-cabin. The quantitative evaluation of PM2.5 transfer characteristic analysis under mechanical ventilation shows that ventilation, penetration and deposition accounted for 69.3%, 22.8%, and 7.9%, of cabin PM2.5 respectively. While under recirculation condition, penetration accounted for 72%, and deposition accounted for 28%.

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